Overview and Case Study of Cryogenic Cooling in Machining of Nickel Based Alloy

N. Badroush[ab], C.H. Che Haron[a], J. A. Ghani[a], M.F.Azhar[a], Nurul Hayati Abdul Halim[ac]*

[a]Department of Mechanical & Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor

*[b]*Center of Human Resource Development & Quality, Academy of Maritime Studies, Tripoli, Libya*

[c]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor

**nordinbadroush@yahoo.com*

ABSTRACT

The application of coolant in machining operations influences the machining performances such as increase tool life, surface roughness and dimensional accuracy, decrease cutting temperatures and amount of power consumed. Therefore, this paper presents an overview of cryogenic machining and a case study on its application in turning Nickel alloy. This study covers the area of tool life, wear and chip formation under dry and cryogenic conditions. The tool wear was measured under the movable optical microscope with reference to ISO 3685-1993 for VBmax = 0.6 mm. Wear and chip measurement were observed under table top SEM and optical microscope. Results show the increment of tool life for 35%, 53% and 30% of cutting speed 75, 90 and 105 m/min respectively under cryogenic over dry conditions. The dominant wear on the coated carbide is the maximum flank wear which ends up the tool life. Adhesion on the flank face is obviously under a dry condition at speed of 90 and 105 m/min over cryogenic. There was gross fracture appeared under dry at 90 and 105 m/min while the only minor fracture appeared under cryogenic at that level of the parameter. The chip thickness under cryogenic is higher than the dry condition. Shear angle shows a positive correlation to chip thickness where the lower angle obtained

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under cryogenic while higher angle obtained under dry condition.The pitch of the chip serration is longer under cryogenic over dry at all cutting speeds.
Keywords:*cryogenic cooling, machining, turning, Nickel alloys*

Introduction

Friction that happens between work piece-cutting tool and cutting tool-chip interfaces during machining cause generation of heat that increases cutting temperatures. The common effects of this conditions; decrease tool life, increase surface roughness and decrease the dimensional accuracy of work piece. This situation is more critical when machining Nickel alloys where more heat would be generated due to higher strength of these materials at high temperatures (Mamidi & Xavior 2012). It is believed that this is happens due to larger volume fractions of strengthening γ precipitates of these alloys than conventional alloys. In addition, they also have poor thermalconductivity, that make them difficult to machine. The heat generated in the cutting zone stays there, thus causing the softening of the cutting tool material. This usually leads to rapid tool wear, and consequently shorter cuttingtool life, and resulted the deteriorated machined surface integrity (Pusavec et al. 2011). The use of proper cutting fluid is known to be very important to control this problem. The most common method is by using conventional cutting fluids. However, many researchers found that they were not sufficient to reduce the temperatures as they fail to penetrate into the chip-tool interface. Dhananchezian et al. 2009 have suggested cryogenic coolant as an alternative due to its excellent cooling ability along with environmental friendliness. Thus, this work focuses on studying the effect of cryogenic cooling when machining Nickel alloys.

Cryogenics

Cryogenic is the discipline and technology of working at temperatures below 120°K with liquid nitrogen (-196°C) andcarbon dioxide (-78.5°C) are the common coolants to be applied. The two gaseousare used for different requirements due to differ considerably with respect to the mechanisms of refrigeration (Busch et al. 2016). Cryogenic cooling is used for effective and fast removal of heat generated during the cutting operations and is used for almost all types of material (Balaji et al. 2015). Many of the studies in cryogenic machining have been conducted during years 2000 onwards as shown in Figure 1. Turning, asshown inFigure 2, is one of the most common operations applying cryogenic cooling system because the cutting tool can be modified or an external nozzle can be pointed at the cutting zone more easily (Shokrani et al. 2013).Compared to conventional cooling,cryogenic cooling gives more advantages such as bettertool life, better chip breaking and chip handling, higher productivity, cheaper productivity cost, environmentally safer as well as healthier for the worker.Yildiz & Albant 2008 revealed that the cryogenic machining increased productivity near to 21.36% in machining of AISI 304 stainless steel compared to conventional cooling, as shown in Figure 3.

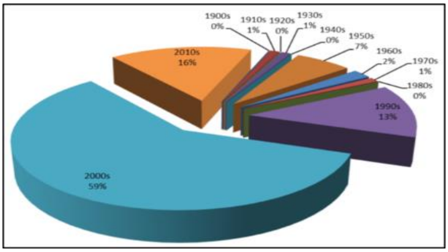

Figure 1: Distribution of the collected papers based on the publication year(Shokrani et al. 2013)

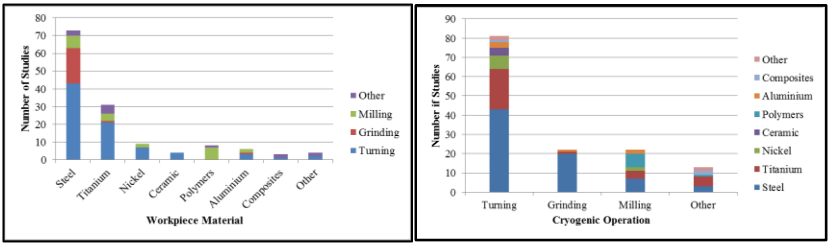

Figure 2: Distribution of the collected studies on cryogenic machining based on the workpiecematerials and cutting operations(Shokrani et al. 2013)

Cryogenic technology

For machining operations, CO_2 and LN_2 are the most exclusively used in cryogenic machining.

Liquid Nitrogen (LN_2)

Figure 4 shows the phase diagram for LN_2. LN_2 is nitrogen in a liquid state at a very low temperature and stored in tanks at very high pressure. When the media enters the ambient temperature and the pressure drops (1.013bars), the nitrogen starts boiling at -196°C. LN_2 absorbs the heat dissolute from the cutting process and evaporates into nitrogen gas and becomes a part of the air. It is safe non-combustible chemical and leaves no harmful residue to the environment since in becomes a part of the of nitrogen in the atmosphere(Stefánsson 2014).

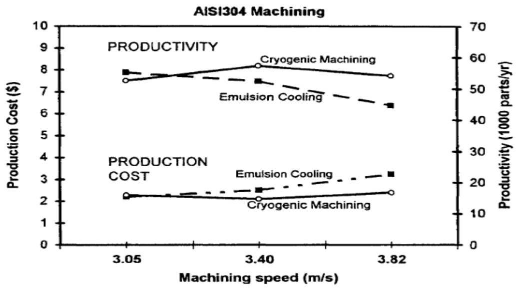

Figure 3: Comparison of production cost and productivity of cryogenic machining withemulsion cooling(Yildiz & Albant 2008)

Carbon Dioxide (CO_2)

Figure 5 shows the phase diagram of CO_2. At pressure from 0 to 5.2 bar and temperature from absolute zero (-273 °C) to -56.6°C, CO_2 can only be at solid or gaseous state. CO_2must be kept at apressure above 5.2 bars so that it will stay in liquid form. CO_2 is stored in a medium pressure tank (MPT) at apressure of 57 bars in liquid form at around 20°C. CO_2 is provided through pressure-resistant pipes to guarantee the same phase of the chemical from the tank to the cutting zone. When the CO_2 exits the pipes and enters the atmospheric pressure, it experiences a major pressure drop, causing it to expand and cool down due to the Joule-Thomsoneffect.The CO_2 cools to -78.5°C and transforms in 40% snow and 60% gas. After CO_2 has served its role as a cutting fluid the chemical sublimates to the air and leaves no residue (Stefánsson 2014).

Cryogenic cooling of nickel based alloy

The nickel super alloys are heat-resistant alloys and able to sustaintheir high mechanical and chemical properties at higher temperatures.They are ideal to be used in power generators and aerospace aero-engine components (Saoubi et al. 2008). Nickel alloy is not a good heat conductor.Hence,heat generated cannot be effectively secludedduring the process through the workpiece and chips. This will increase the cutting temperature which lead to severe tool wear and bad surface quality. The hardness of the nickel alloys is also increases with the increases in the temperatures (Shokrani et al. 2012). Most researchers have reported (**Error! Reference source not found.**) that the machinability of nickel alloys with cryogenic cooling has enhanced and reduced machining cost significantly. However, only 6.5% of the studies focused on turning nickel alloys with only two experiment on the milling of Udimet 720 (Shokrani et al. 2013). Wang & Rajurkar (2000) has studied the effect of cryogenic cooling on the cutting tool through a cap placed over the cutting insert. Improvementon the surface finish and tool life were significant.Figure 6 shows the H13A tool wear progress curves for machining Inconel 718 with and without LN_2 (Wang et al. 2003).The insert showed severe tool wear without the use of LN_2 cooling. From a comparison study by Fernandez (2014), less tool wear was noticed when machine Inconel 718 under cryogenic machining. The tool life increased by 34,6%, 55,9%, and 75,4% compared to emulsion based, cold air and dry machining respectively as shown in Figure 7.

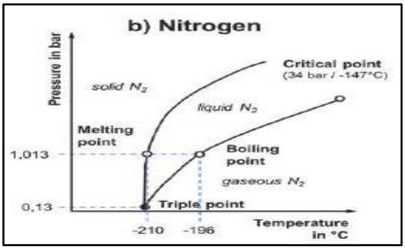

Figure 4: Phase diagrams for LN_2 (Stefánsson 2014)

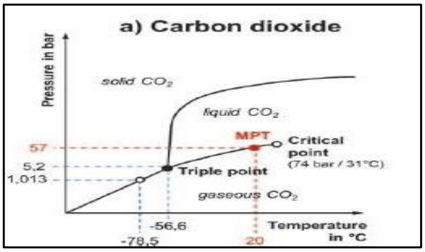

Figure 5: Phase diagrams for CO2 (Stefánsson 2014)

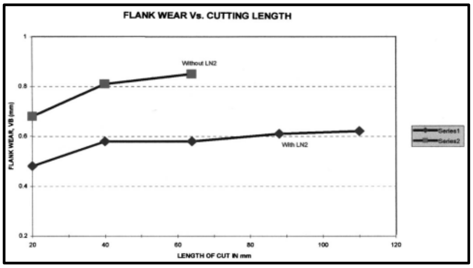

Figure 6: Tool wear in machining Inconel 718. (Wang et al. 2003)

Pusavec et al. (2011) reported that correct distribution of LN_2 into the cutting zone improves the surface integrity of the Inconel 718. Hence,resulting in up to a 63% reduction in the machining time. This reduction inthe tool changing time has a big contribution to the overall costof production in conventional machining. From the result inFigure 8, it is proven that cryogenic machining is less expensive than conventional machining (Pusavec & Kopac 2011).

Wang et al. (2003) in Figure 9illustrates the setup of hybrid machining process integrated between plasma heating and LN_2 cooling of the cutting tool in turning of Inconel 718. This approach led to 250% reduction in the surface roughness, 156% longer tool life and produced 30%-50% less cutting forces in comparison to dry machining. Jawahir et al. (2012) as shown in

Figure 10indicated that the cryogenic cooling significantly resulted with a smoother surface,which produces a better surface roughness compared to dry machining.

Table 1 Summary of studies on the effects of Cryogenic Cooling in Machining of Inconel alloys (S: surface integrity, F: cutting forces, L: tool life, T: cutting temperature)

No	Year	Cutting speed m/min	Feed rate mm	Depth of cut mm	Condition	Operation	Tool material	Area of Study			
								S	F	L	T
1	Wang et.al 2000	133.8	0.1	0.5	NL2	Turning	PCBN H13 A	X		X	
2	Wang et al. 2003	312	0.109	0.76	NL2	Turning	Silicon carbide WG-300	X	X	X	
3	Saumya S. et.al 2005	45 60 80	0.2	1.5	NL2	Turning	Coated (TiAlN) CP250 Uncoated CP883			X	
4	Kopac et.al 2009	45	0.15	0.50	NL2	Turning	Uncoated carbide WC	X		X	X
5	T. Arunkarthik et.al 2010	44 64 102	0.5 0.1 0.15	0.5 1 1.5	Cooling and NL2	Turning	Coated Ti – AIN		X		X
6	F.Pusavec et al 2011	90	0.25	1.2	NL2	Turning	(tungsten carbide) and metal binder WC-Co	X	X		
7	F.Pusavec et al 2010	60	0.05	0.63	NL2 MQL	Turning	TiAlN Coated WC			X	
8	Jawahir et.al 2012	60	0.075	0.77	NL2	Turning	Carbide CNMG 120408	X			X
9	Sivaprakasam et.al 2013	30 40 50	0.05 0.10 0.15	0,50 0,75 1	NL2	Turning	Super hard tool CBN and PCBN	X		X	
10	N.G. Patil et.al 2014	70 85 100 115 130	0.10 0.17 0.24 0.32 0.40	0.5	Dry Compressed CO2	Turning	Coated carbide PVD (TiAlN)	X		X	
11	Shokran et al. 2012	50	0.03	0.5	NL2	End milling	TiAlN Coated WC	X		X	

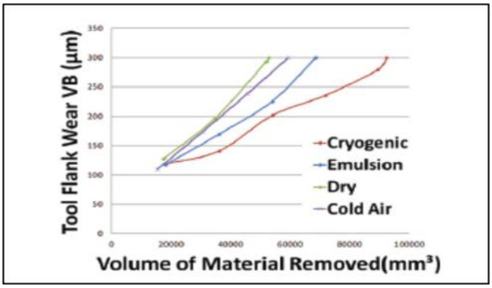

Figure 7: Evolution of tool life in dry, oil-based emulsion, cold air and cryogenic turning of Inconel 718(Fernandez et al. 2014)

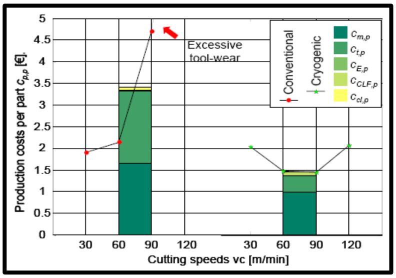

Figure 8: Comparison on production costs (Pusavec & Kopac 2011)

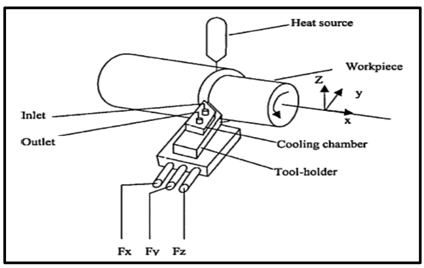

Figure 9: Setup of the hybrid machining process(Wang et al. 2003)

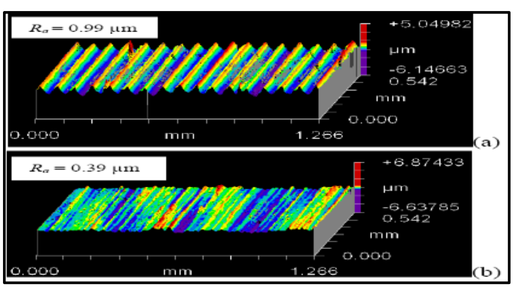

Figure 10: Surface topology and roughness of machined Inconel 718 samples from (a) dry, and (b) cryogenic machining (Jawahir et al. 2012)

Figure 11 proof that the cryogenic coolingwill generate broadening peaks, demonstrating the increased grain refinement on the surface and subsurface of machined material as compared to dry machining. Another study is by Thamizhmanii et al. (2015)indicated that cryogenic turning process of Titanium alloy using cryogenically treated inserts has better surface roughness than Inconel 718. Patilet al. (2014) has found lower surface roughness in CO_2 machining due to areduction in tool nose wear.However, highermicro hardness of the machined surfaces and sub-surfaceswere produced. The micro hardness in therange of 495 HV to 505 HV against the bulk material hardness of 380HV is probably due to cold work hardening. Dry turning also produced higher microhardnessof the machined surfaces, as shown in Figure 12(Patil et al. 2014).

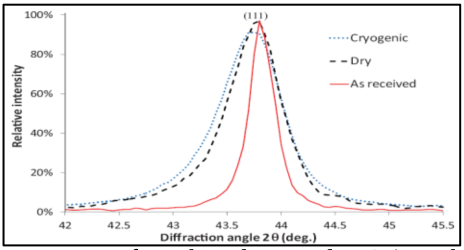

Figure 11: XRD patterns of machined Inconel 718 (Jawahir et al. 2012)

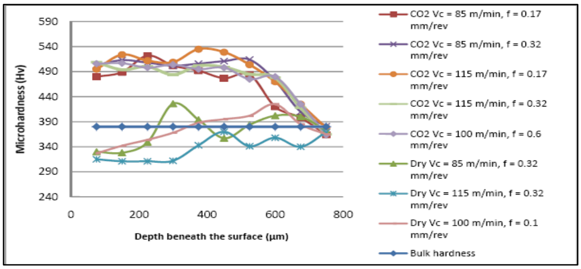

Figure 12: Microhardnessvariation with depth under the machined surface (Patil et al. 2014)

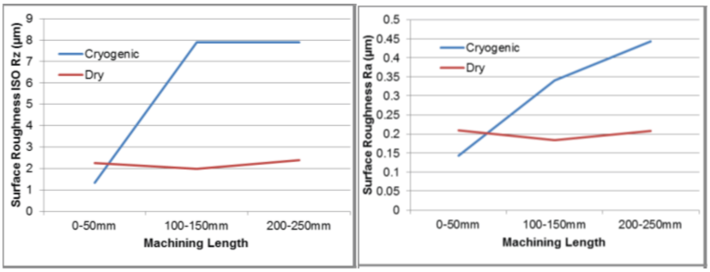

Figure 13: Comparison of surface roughness under cryogenic and dry conditions (Shokrani, Dhokia, Newman, et al. 2012)

Shokrani et al. (2012) use TiAlN coated solid carbide tools inend milling of Inconel 718 underLN_2 cryogenic environment. It resulted in 33% and 40% reduction in Ra and ISO Rz surface roughness as compared to dry machining(

Figure *13*). Zhang et al. (2016) proved that the cryogenic machining reduced tensile stresses on the surface and subsurface of the machined workpiece than dry machining,as shown in Figure 14.

Case study

The main purpose of this study is to investigate the effects of different cutting parameters on the cutting tool performance and surface roughness when machining Inconel 718 alloys. Dry and cryogenic cooling with LN_2has been used in this study.

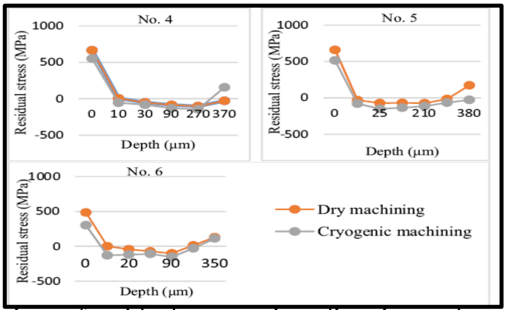

Figure 14: Comparison of residual stresses in y direction under cryogenic and dry conditions(Zhang et al. 2016)

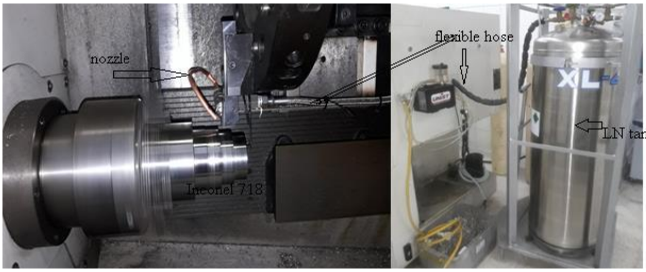

Figure 15: The cryogenic delivery setup during the turning process

Experimental Procedure

Machining experiments were performed on Colchester Tornado T4 two axes CNC lathe machine. Machining parameters such as cutting speed, depth of cut and feed rate were deployed as in Table 2.The cryogenic delivery setup during the turning operation is shown in Figure 15. To deliver the LN_2 to the cutting zone, a flexible hose was connected to the LN_2 tank and a copper pipe was used as a nozzle pointing to the cutting zone. The tool insert used was KC5510 coated carbide insert from Kennametal as shown in Figure 16. The measurement devices included Mitutoyo tool maker's microscope was used to measure all tool wear and Mitutoyo surface tester SJ-310 was used to determine workpiece surface roughness (Ra) as shown in Figure 17.

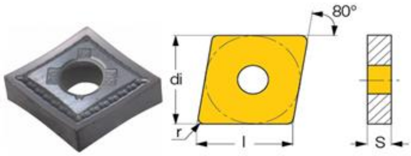

Figure 16: Cutting insert and tool's geometry

Table 2: Machining parameters

Factor	Cutting Speed, V (m/min)	Feed rate, f (mm/rev)	Depth of Cut, a (mm)
Level 1	75	0.2	0.25
Level 2	90	0.12	0.5
Level 3	105	0.05	0.25
Condition	Cryogenic and Dry		

Figure 17: (a) Mitutoyo Surftest SJ-310 portable surface roughness tester (b) Placement ofsurface roughness tester on the workpiece surface

Tool Wear and Chip Formation

Tool wear and chip formation study were conducted using equipment as in Figure 18. The tool wear limit criteriaswere referred to ISO 3685-1993.

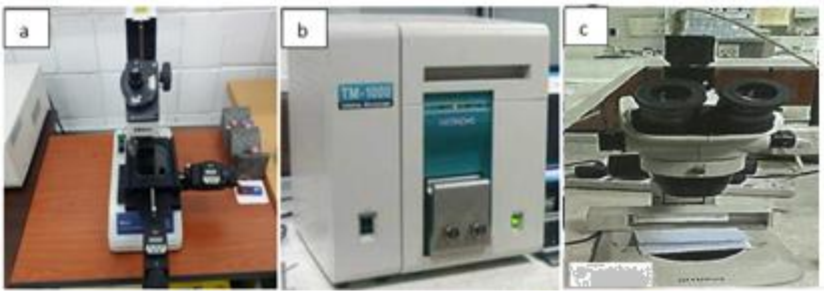

Figure 18: Equipment for tool wear and chip formation study

a) Optical Microscope Mitutoyo 176-811E: used to measure the flank wear progression throughout the experimental runs.
b) Tabletop SEM Hitachi TM100: used to image the tool and the formation of wear with ability to see objects at 10000 times magnification.
C) Olympus SZ61 stereo microscope: used to observe and capture the tool flank wear image.

Results and Discussion

Wear Progression and Tool Life

Results from wear measurement wererepresents into wear progression as in Figure 19.Maximum flank wear was found to be the limiting criteria for the end of the tool life at both dry and cryogenic conditions.

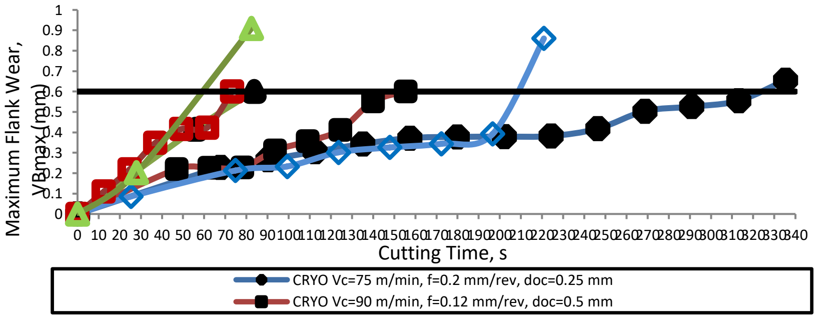

Figure 19: Wear Progression of Maximum Flank Wear over Cutting Time under Dry and Cryogenic Conditions

From Figure 19, the wear progression is longest for cutting speed 75 m/min, followed by 90 m/min and 105 m/min under both conditions. The steady state region is longer at 75 m/min followed by 90 m/min. However, at 105 m/min, it experienced very short time for the steady state which then rose to the region of catastrophic failure. The coated carbide stays within steady state region at thelonger time under thecryogenic condition, then went up to catastrophic failure region where tool life was measured byreference of ISO 3685-1993 for maximum flank wear of 0.6 mm. The tool life of the coated carbide represents in Figure 20. Cryogenic machining has improved tool life under all parameters with apercentage from 30 % to 53 % increment.

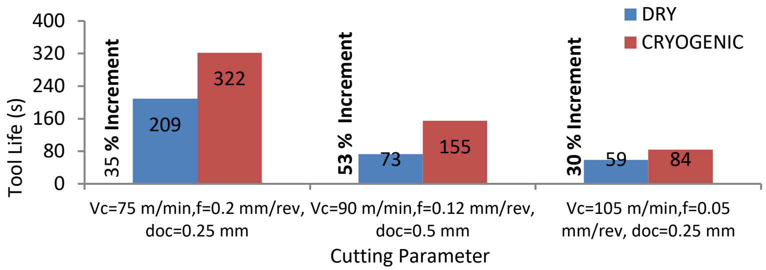

Figure 20: Tool Life of Coated Carbide under Dry and Cryogenic Conditions

The gross fracture of coated carbide at 90 and 105 m/min under dry condition appears. The fracture started from theedge of the tool down to the flank area which exposed the substrate of the coated carbide. However, wear under cryogenic are more stable and no gross fracture appear. At 90 and 105 m/min, minor fracture along the cutting edge appears under thecryogenic condition as in Figure 21.The minor fracture might due to the chip hammering which also found by Cantero et al. 2013. The fractures are worst under dry compared to thecryogenic condition.

Figure *22* clearly shows the burnt mark on the tool just beside the wear at the flank area on the tool coating. Yazid et al. 2009 reported the same burnt mark on coated carbide under dry cutting. However, there is no burnt mark on the tool under cryogenic condition.

Chip Formation

The formation of the chips is different depending on the cutting parameter. The difference of the types of chips producedis presentedinFigure 23.

<u>Chip Thickness, Chip Thickness Ratio & Shear Angle</u>

The measurement of the chip thickness and pitch were conducted under Scanning Electron Microscope (SEM). The variation values on chip thickness due to thevarious value of feed rate used on each different speed during the experiment. Figure 24shows the measured chip thickness and chip thickness ratio of the segmented chip at different optimized parameter.

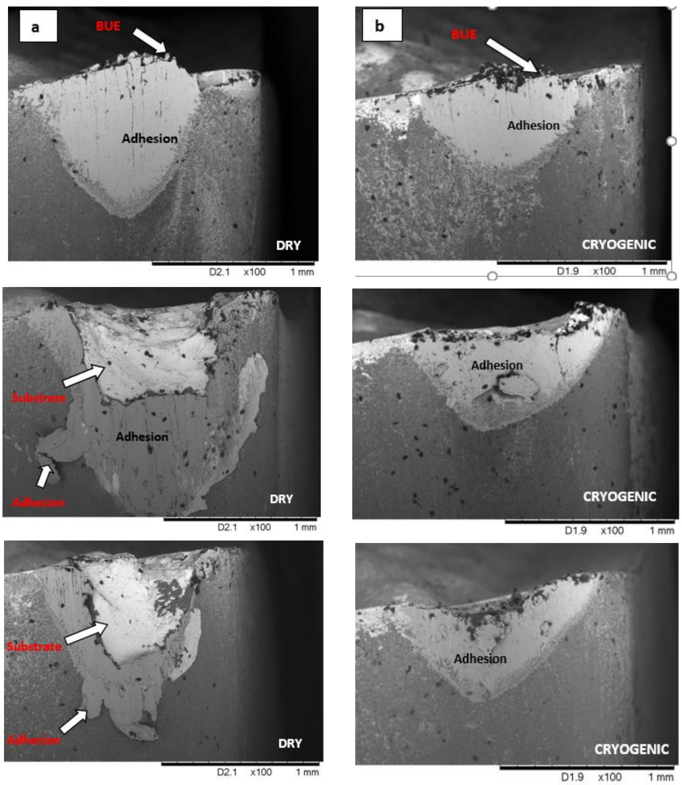

Figure 21: Wear Mechanisms for Dry and Cryogenic Conditions for cutting speed a) 75 m/min, b) 90 m/min and c) 105 m/min (at 100x enlargement)

The chip produced under cryogenic condition are thicker than thedry condition. Kaynak (2014) also reported the same result of athicker chip formed under thecryogenic condition, which could lead to increase in the cutting force component. From the view of chip thickness ratio, as thethicker chip is formed then the thickness ratio will decrease. The chip thickness ratio(r) relates to the shear angle (Ø), which was calculated by formulation from Merchant 1945 and presentedin Figure 265.

Pitch

The pitch considered as the distance between two successive teeth of the serrated chip. Figure 276shows the measured pitch of the chip for thedry and cryogenic condition.The pitch of chip serration relates to the chip segmentation frequency (Dong et al. 2011) (Zhang et al. 2013) (Pawade & Joshi 2011). For this study, pitch for cryogenic is longer than thedry condition and it becomes shorter when ahigher level of speed applied. As the pitch becomes shorter, it will increase chip segmentation frequency (Pawade & Joshi 2011). Thus, the high frequency of segmentation leads to fluctuation of cutting force components and major vibration that damaging to the stability of whole machining system (Zhang et al. 2013). In general, it is clearly observed the positive impact of cryogenic over dry condition from the view of chip segmentation.

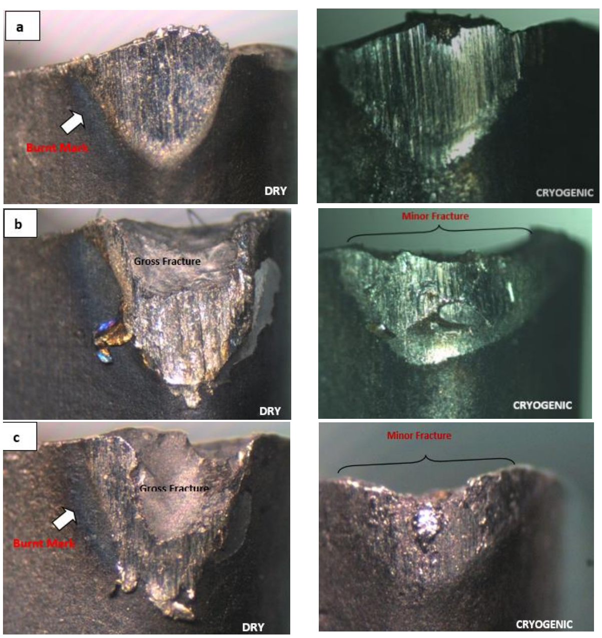

Figure 22: Wear Mechanisms for Dry and Cryogenic Conditions for cutting speed a) 75 m/min, b) 90 m/min and c) 105 m/min under Optical Microscope observation with 5x Enlargement

	Vc = 75 m/min, f = 0.2, doc = 0.25	Vc = 90 m/min, f = 0.12 mm/rev, doc = 0.5 mm	Vc = 105 m/min, f = 0.05, doc = 0.25
DRY			
	Snarled Helical	Snarled Spiral	Continuous Ribbon
CRYOGENIC			
	Helical	Snarled Ribbon	Connected Arc

Figure 23:Chip formation under Dry and Cryogenic Conditions

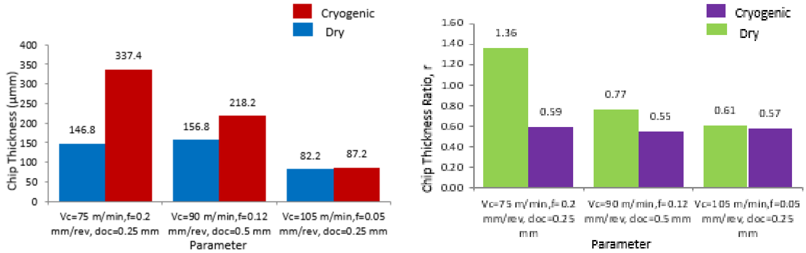

Figure 24: Chip Thickness and Chip Thickness Ratio under Dry and Cryogenic Conditions

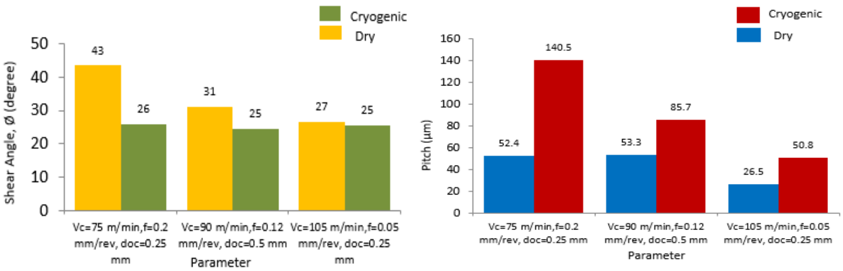

Figure 265:Chip Shear Angle under Dry and Cryogenic Conditions

Figure 276:Measured Pitch under Dry and Cryogenic conditions

Conclusion

This review shows that cryogenic machining increases hardness and compressive residual stress, and reduces thesurface roughness of nickel alloy. Hence, it offers a process that improves the final part performances via better machined surface integrity, emphasizing the benefits and the need for implementing cryogenic cooling in all machining applications.After the experimental results discussed, there are several conclusions can be made;

1. This study has proved that cryogenic machining is able to improve tool lives of the coated carbide by 35%, 53% and 30% at cutting speed 75, 90 and 105 m/min respectively. It also has the ability to reduce the progression of flank wear, adhesion and also gross fracture.
2. The chip thickness under cryogenic is larger than dry condition, but it becomes thinner at ahigher level of speed which shows theability of cryogenic machining at high speed. Formation of the thickness of the chip is proven by the shear angle which the angle is lower under cryogenic that results to thicker chip. The measured pitch of the serration on the chip free face has proven that cryogenic condition produces ahigher pitch, 140.5μm, than dry at 75 m/min and shorter, 50.8μm, at high speed of 105 m/min.

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